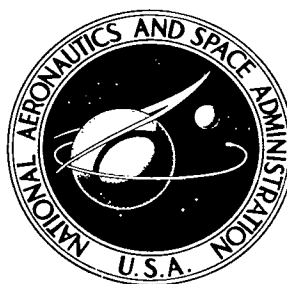


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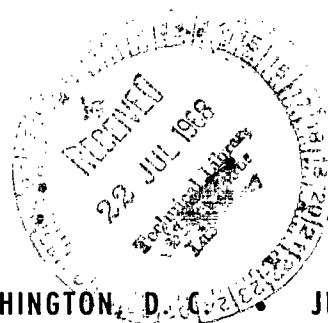


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FRICITION AND WEAR UNDER
FRETTING CONDITIONS OF MATERIALS
FOR USE AS WIRE FRICTION DAMPERS
OF COMPRESSOR BLADE VIBRATION

by Max A. Swikert and Robert L. Johnson

*Lewis Research Center
Cleveland, Ohio*



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

Friction dampers are required to reduce the magnitude of vibrational stresses in high-aspect-ratio blading of compressors for advanced aircraft turbine engines. Fretting is a common problem with all types of friction dampers. Fretting experiments with simulated wire-lace blade damping were conducted with Inconel 600. Experiments were run with or without oxide coatings in contact with maraging steel. Although two methods were used to form the oxide, high friction and low wear occurred with both. Further wear experimentation with oxidized material rubbing against itself showed that friction and wear were decreased by operation at a higher temperature (500° F or 260° C).

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FRICION AND WEAR UNDER FRETTING CONDITIONS OF MATERIALS FOR USE AS WIRE FRICTION DAMPERS OF COMPRESSOR BLADE VIBRATION

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SUMMARY

Friction dampers are required to reduce the magnitude of vibrational stresses in high-aspect-ratio blading of compressors for advanced aircraft turbine engines. Wire sections threaded through holes in the external portion of the blade and loaded by centrifugal forces during operation can provide effective damping. The life of such dampers is limited by fretting wear between the wire and the blade. The effectiveness of damping is increased if friction is high.

A series of fretting experiments at room temperature showed that the wire of a chemically oxidized nickel-base alloy (Inconel 600) had high friction and low wear in contact with a compressor blade of maraging steel. Both friction and wear were decreased by operation at a higher temperature (500°F ; 260°C). The Inconel 600 wire samples that were oxidized in high-temperature air also performed well. These results suggested that films regenerated in service will sustain effective damping.

INTRODUCTION

Advanced supersonic aircraft engines require that engine compressors operate at maximum efficiency. Designs for aerodynamically efficient, high-aspect-ratio compressor blades necessitate damping of vibrational stresses, and various methods have been used for this purpose.

One experimental method of damping compressor blade vibration is to thread wire segments through holes in the airfoil (refs. 1 to 3). During rotation of the compressor, centrifugal force loads the wire against the compressor blade. Damping is provided by frictional force between the wire and the blade (fig. 1). Proper selection of a material combination for the blade and the wire is essential for this method of damping, because fretting wear at the point of contact between the blade and the wire limits the life of both.

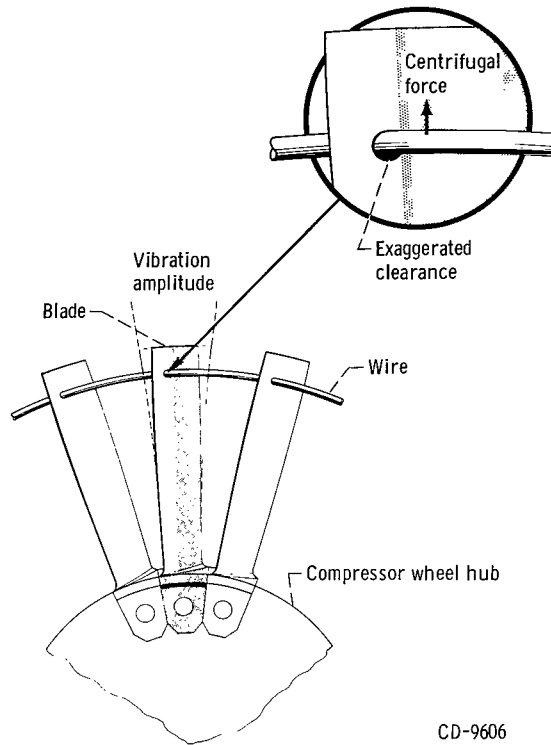


Figure 1. - Schematic diagram of compressor blades with damping wire.

Cracks form radially outward on the blade from these wear areas. The desired material combination must therefore provide high friction for maximum damping and low wear for maximum life. Also, the wire must have a suitable tensile strength to withstand the stresses in rotating compressors.

Sliding conditions during fretting accelerate the oxidation of metals in the contact area. The reaction products can be either beneficial or detrimental, depending on the shear and the other properties of the oxide formed (ref. 4). Prior to operation, beneficial oxides may be formed on metals by treating them in molten sodium hydroxide or heating them in air.

The objective of this investigation was to study the fretting behavior of metals that can provide high friction and low wear under conditions simulating the fretting problem of compressor blade vibration. Coatings such as oxides were used to improve the friction and wear properties of metals. Experiments were performed to show the fretting behavior of several materials that have been used or are being considered potentially useful for damping compressor blade vibration.

MATERIALS

Materials for advanced aircraft compressors are selected on the basis of thermal and mechanical properties. Thermal properties such as oxidation resistance and high-temperature strength are important. The mechanical properties of two compressor blade materials, maraging steel and titanium (Ti)- 6 aluminum (Al)- 4 vanadium (V) alloy, are given in table I along with those of two compressor blade damping-wire materials, Inconel 600 and Ti-6Al-4V alloy. The titanium alloy blade and wire have the same

TABLE I. - TYPICAL VALUES FOR PROPERTIES OF MATERIALS
USED WITH BLADE DAMPING

[From literature unless otherwise indicated.]

| Material | Nominal composition | | Tensile strength, N/m^2 | Hardness | | Density, kg/m^3 | Modulus of elasticity, N/m^2 |
|----------------|---------------------|-------|---------------------------|----------|-------------------------|-------------------|------------------------------------------------------|
| | Alloying elements | wt. % | | Brinell | Rockwell A ^a | | |
| Ti-6Al-4V | Titanium | 90.0 | 82.7×10^7 | 346 | 69.5 | 4480 | 10.3×10^{10} to 12.0×10^{10} |
| | Aluminum | 6.0 | to | | | | |
| | Vanadium | 4.0 | 124.0×10^7 | | | | |
| Inconel 600 | Nickel | 76.0 | 77.3×10^7 | 161 | 51.5 | 8430 | 21.4×10^{10} |
| | Carbon | .04 | to | | | | |
| | Manganese | .20 | 103.2×10^7 | | | | |
| | Iron | 7.20 | | | | | |
| | Sulfur | .007 | | | | | |
| | Silicon | .20 | | | | | |
| | Copper | .10 | | | | | |
| | Chromium | 15.8 | | | | | |
| Nickel 200 | Nickel | 99.5 | 35.9×10^7 | 114 | 40.0 | 8890 | 20.6×10^{10} |
| | Carbon | .06 | to | | | | |
| | Manganese | .25 | 51.6×10^7 | | | | |
| | Iron | .15 | | | | | |
| | Sulfur | .005 | | | | | |
| | Silicon | .05 | | | | | |
| | Copper | .05 | | | | | |
| Maraging steel | Iron | 69.3 | 144.8×10^7 | 450 | 74.5 | 8030 | 18.8×10^{10} to 18.9×10^{10} |
| | Carbon | .03 | | | | | |
| | Cobalt | 7.5 | | | | | |
| | Molybdenum | 5.0 | | | | | |
| | Titanium | .20 | | | | | |

^a Measured with Rockwell hardness tester.

composition and physical properties. Table I also gives the mechanical properties of commercially pure nickel (Ni 200), which does not have suitable mechanical strength for compressor blade damping wire but was included for comparison.

In this investigation, Inconel 600 was selected as a candidate material for compressor damping wires. Previous work (ref. 5) revealed that nickel oxides are formed at the areas of contact during sliding and that nickel oxides can be formed on Inconel (ref. 6).

Ti-6Al-4V alloy is of interest because of its high strength and low density properties (table I). Unreported experience indicates that difficulty with wear and galling have been encountered with this material as a compressor blade damper; therefore, it was included for reference purposes.

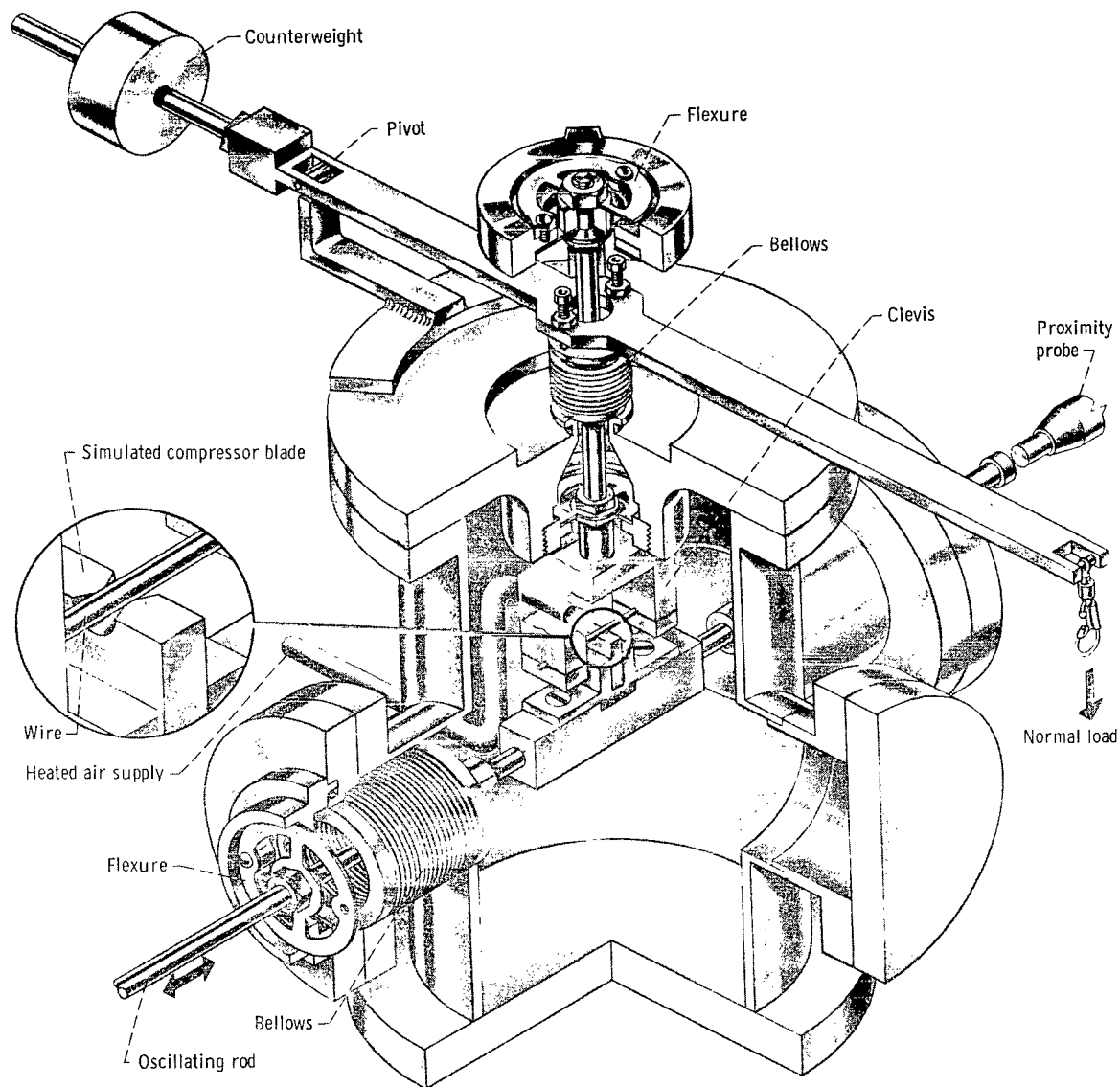
APPARATUS

The apparatus used in this investigation is shown in figure 2. The wire test specimens were 1/16 inch (1.59 mm) in diameter and 2 inches (50.8 mm) long, and the rectangular specimens (simulated compressor blades) were 5/8 inch (15.9 mm) by 1/2 inch (12.7 mm) by 1/8 inch (3.18 mm) and had a 0.040-inch- (10.2-mm-) radius groove on one end to simulate the hole in a compressor blade. The radius groove was beveled on each side to make the width of the 0.040-inch- (10.2-mm-) groove section 1/16 inch (1.59 mm). The groove configuration simulates a compressor blade and provides for optical examination of the wear area. The 2500-gram load used produced an initial Hertz stress of 58 000 psi (40.0×10^7 N/m²). These stresses of damping wires on blades have been used in experimental compressors. The damping wire was the same size as that used in experimental compressors (ref. 3).

Inside the test chamber, the rectangular specimen was mounted on a horizontal rod supported on each side of the chamber with bellows and flexure assemblies (fig. 2). The rod was oscillated from one end by a magnetic driver located outside the test chamber and powered by an audio oscillator and power amplifier. The displacement of the wire was obtained and controlled by the power amplifier and oscillator gain controls. The displacement was monitored with a proximity probe tandem to the support rod and opposite the driver end.

Inside the chamber, the wire specimen was fastened to the ends of a clevis as a fixed beam. The clevis was supported from a vertical rod with a bellows and flexure assembly that was mounted perpendicular to the horizontal oscillating rod. The wire specimen, parallel to the oscillating rod, was loaded against the radial groove of the rectangular specimen by means of a lever between the flexure support and bellows on the vertical rod, located at the top and outside the test chamber (fig. 2).

Heated air was supplied to the test chamber through a 1/4-inch- (6.35-mm-) outside



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Figure 2. - Fretting apparatus.

diameter stainless-steel tube and was directed across the test specimen. The temperature was measured by means of a thermocouple inside the test chamber between the air outlet and the specimen, 1/8 inch (3.18 mm) from the air outlet, in the air stream. A stainless-steel coil inside a tube furnace heated the air as it passed through.

PROCEDURE

Specimen Preparation

Metallographic polishing and cleaning techniques were used to prepare the specimens as follows: They were first polished with 2-0 grit metallographic polishing paper to remove machine and die drawing marks. The surfaces were then polished with moist levigated alumina and a clean white flannel cloth until the cloth was no longer discolored by the polishing process. Distilled water and another clean white cloth were used to remove the levigated alumina. The specimen surfaces were then rinsed with 100 percent ethyl alcohol to absorb the water. For those specimens requiring an oxide coating, a second rinse with distilled water and alcohol was given after the oxidation treatment.

Two methods were used to form the oxide film on the specimens. One method consisted of heating the specimens in an air furnace at 1600° F (871° C) for 12 hours, and the second consisted of heating the specimens at 1200° F (649° C) for 3 hours in molten sodium hydroxide, which was removed after the treatment by a rinsing in running tap water for 1 hour.

The specimens were mounted on the apparatus and dry air (heated to the desired operating temperature) was allowed to flow across them. The air flow in all experiments was 20 cubic feet per hour ($1.57 \times 10^{-4} \text{ m}^3/\text{sec}$). Before the 500° F (260° C) experiments were started, the air temperature was allowed to stabilize.

Test Procedure

Experiments were run for 24 hours at a frequency of 68 hertz and under a load of 2500 grams at a fixed power input. The wire displacement from the proximity probe provided a relative measure of the friction, and the superimposed peaks gave an indication of variable behavior (such as surface welding) in the friction process. Microscopic examination was made of all materials before and after each experiment. Wear-scar measurements were made on the specimens after each experiment with surface-profile measuring equipment and an optical microscope. X-ray diffraction was used to identify the oxide films and wear debris.

RESULTS AND DISCUSSION

Results of previous studies by the authors (refs. 5 and 6) indicated that nickel base alloys in sliding contact form nickel oxide at the sliding interface. Reference 6 disclosed that Inconel in particular has the desired high friction and that wear (initially high) is reduced 85 percent or more after an oxide film is formed at the area of contact in sliding. Oxides can be formed on wear surfaces prior to operation and reduce the initial wear (ref. 6).

In an experimental compressor with blades and damping wire of Ti-6Al-4V alloy, extreme wear and galling were encountered. That result was not surprising because titanium is known to have very poor friction and wear properties. Typical friction and wear results showing the poor friction are given in references 7 and 8.

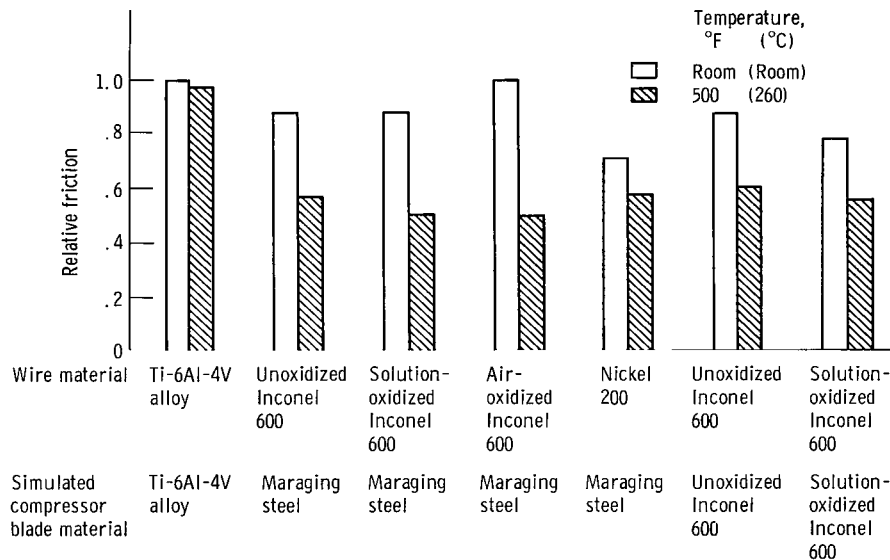


Figure 3. - Relative friction of various material combinations sliding in oscillating motion. Frequency, 68 hertz; load, 2500 grams; atmosphere, air.

The results of fretting experiments run with Ti-6Al-4V alloy are shown in figures 3 and 4. In all experiments, only relative friction measurements are reported, and the room-temperature experimental value for the Ti-6Al-4V alloy is presented as 1.0 for the purpose of comparison.

Figure 4 presents quantitative measures of the wear on the damper wire and shows that the Ti-6Al-4V alloy wear was 34.2×10^{-7} cubic centimeters per cycle. Also, a photomicrograph of the wear scar is shown in figure 5(a). The adhesion and metal transfer of titanium sliding against itself is discussed in reference 7. The fretting produced wear

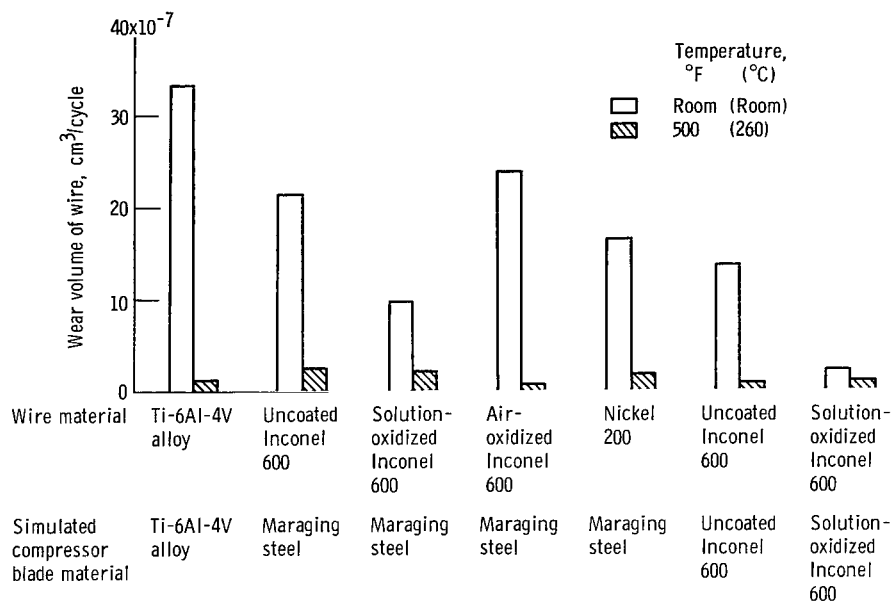


Figure 4. - Wear of various material combinations sliding in oscillating motion. Frequency, 68 hertz; load, 2500 grams; atmosphere, air.

debris (as seen in fig. 6(a)), which appeared as chips with sharp edges. The wear at 500° F (260° C) was very small as compared with that at room temperature.

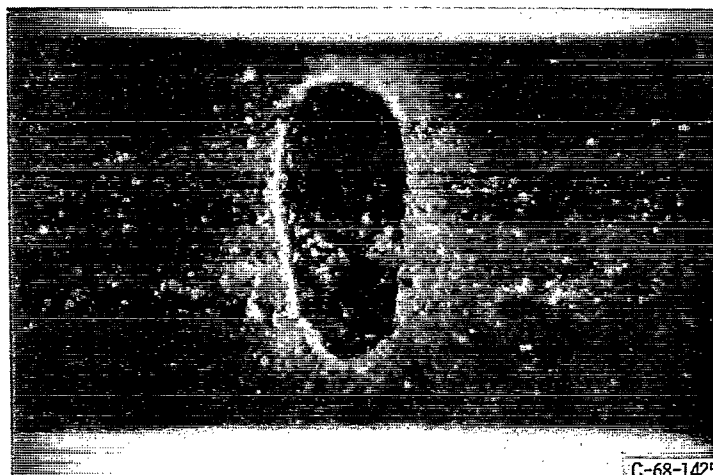
In some compressor designs, maraging steel is used as a blade material. Inconel 600 was selected as a potential wire material to minimize fretting wear and to obtain high friction with the maraging steel. Experiments were conducted with Inconel 600 rubbing against maraging steel for three surface conditions: (1) untreated Inconel 600 wire, (2) Inconel 600 wire oxidized in molten sodium hydroxide, and (3) Inconel 600 wire oxidized in air. For comparison, nickel 200 (commercially pure nickel) was also run to evaluate the possible effects of alloying for Inconel 600 and on the known nickel oxide formation properties of nickel 200 (ref. 5).

X-ray diffraction data obtained with the Inconel 600 and the oxide films formed are shown in table II. With all Inconel 600 materials (treated or untreated), a pattern for the base material (nickel-chrome solid solution) was found before experiment. Nickel oxides, formed with both methods of treatment, and a cubic form of chromium oxide (Cr_2O_3), observed on the air-oxidized Inconel 600, were identified. The Inconel 600 oxidized in molten sodium hydroxide showed a weak indication of gamma nickel hydroxide ($\text{NiO}(\text{OH})$).

The results of the fretting experiments with maraging steels are shown in figures 3 and 4. At room temperature, the friction of these materials was high, as desired for blade damping. At 500° F (260° C), the friction was one-half to two-thirds of that at room temperature.



(a) Ti - 6Al-4V alloy wire sliding against simulated compressor blade of same alloy.

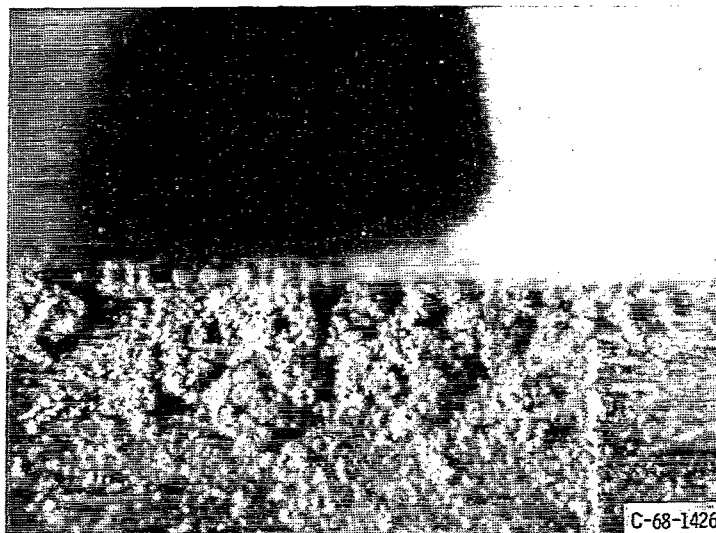


(b) Molten sodium hydroxide oxidized Inconel 600 wire sliding against simulated compressor blade of maraging steel.

Figure 5. - Fretted area on wire of two materials sliding in oscillating motion for 24 hours. Frequency, 68 hertz; load, 2500 grams; atmosphere, air; room temperature.



(a) Ti - 6Al-4V alloy wire sliding against simulated compressor blade of same alloy.



(b) Molton sodium hydroxide oxidized Inconel 600 wire sliding against simulated compressor blade of maraging steel.

Figure 6. - Loose fretting debris accumulated on apparatus from two materials sliding in oscillating motion for 24 hours. Frequency, 68 hertz; load, 2500 grams; atmosphere, air; room temperature.

TABLE II. - QUALITATIVE OBSERVATIONS OF SURFACE CONDITIONS
OF MATERIALS USED IN FRETTING EXPERIMENTS

[Tested for 24 hr of sliding in an oscillating motion; frequency, 68 Hz; load, 2500 grams; atmosphere, air; room temperature.]

| Material | X-Ray identification | | Surface appearance |
|--------------------------------|--------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------|
| | Specimen before experiment | Wear debris after experiment | |
| Ti-6Al-4V alloy ^a | ----- | Titanium oxide (TiO ₂) | Excessive abrasive wear |
| Inconel 600 wire ^b | Nickel-chrome solid solution | ----- | Slight metal transfer at edges of wear area; visible surface film |
| Uncoated ^b | | ----- | |
| Solution oxidized ^b | | Iron-nickel solid solution; iron oxide (FeO); and complex hydrated nickel oxide (4Ni(OH) ₂ · NiO(OH)) | Uniform surface film; no visible metal transfer |
| Air oxidized ^b | Nickel-chrome solid solution; nickel oxide (NiO); and cubic chromium oxide (Cr ₂ O ₃) | Iron-nickel solid solution; and iron oxide (Fe ₃ O ₄) | Uniform surface film; no visible metal transfer |
| Nickel 200 ^b | ----- | Iron-nickel solid solution; iron oxides (FeO and Fe ₃ O ₄); and nickel oxide (NiO) | Uniform surface film; no visible metal transfer |

^aRun against Ti-6Al-4V alloy.

^bRun against maraging steel.

^cProbable identification.

The wear debris identified is presented in table II. These results show that lower iron oxides are formed in fretting. The lower iron oxides in sliding friction experiments are beneficial in lubrication (ref. 4). The friction for the nickel 200 is 20 to 30 percent lower than that for the Inconel 600 wire (treated or untreated) at room temperature, and at 500° F (260° C) the friction is about the same as that for the Inconel 600 at room temperature.

The wear in all experiments with maraging steel at room temperature was much lower than the wear for the Ti-6Al-4V alloy (fig. 4). A typical axial profile trace of a wire wear scar for Inconel 600 after 24 hours is shown in figure 7. The Inconel 600 wire

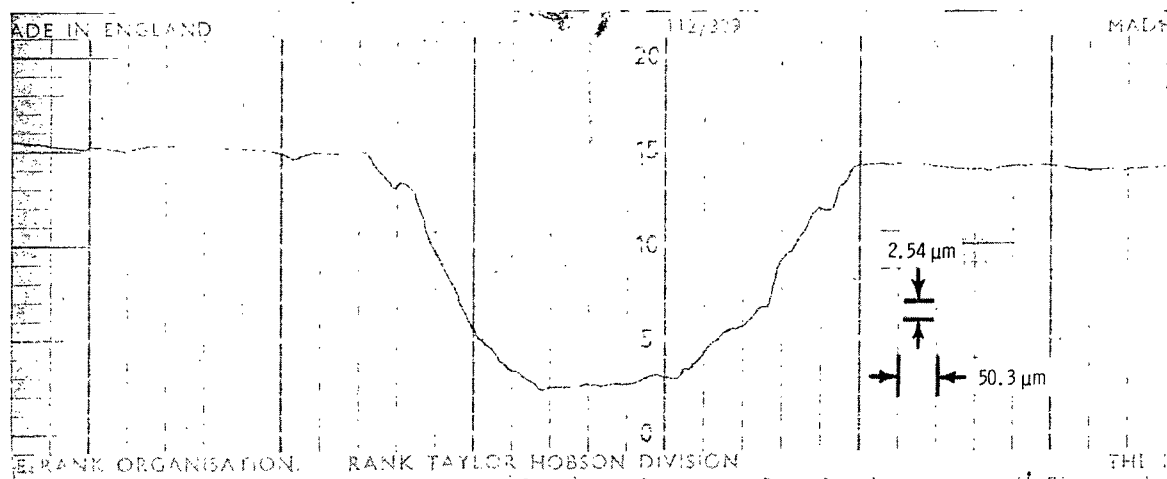


Figure 7. - Typical axial profile trace of wear scar of Inconel 600 wire after sliding in oscillating motion for 24 hours. Frequency, 68 hertz; load, 2500 grams; atmosphere, air; room temperature.

oxidized in molten sodium hydroxide showed the lowest wear at room temperature and that of the wire oxidized in air was slightly higher than the wear of the unoxidized Inconel 600 wire. Figure 5(b) shows the wear scar of the molten sodium hydroxide oxidized Inconel 600 wire after the experiment. The wear debris, a fine powderlike material, is shown in figure 6(b) for the same experiment. Visual observation of the oxide film on the wire before the experiments indicated a coarse oxide on the air-oxidized Inconel 600 as compared with the more adherent fine oxide on the Inconel 600 wire oxidized in molten sodium hydroxide.

In some instances, a beneficial modification for the compressor blade could be made with an insert in the blade for the damping wire to rub against instead of against the blade material itself. For example, an insert of a material having improved wear properties could be mounted in a Ti-6Al-4V blade. Also, further evaluation of the fretting problem required the determination of whether or not more wear reduction could be gained by using combinations of like materials with nickel oxide forming properties. The friction and fretting wear of two like material combinations are shown in figures 3 and 4. The friction values of both the Inconel 600 rubbing against itself and the sodium hydroxide oxidized Inconel rubbing against itself are in the same range as the friction of these materials rubbing against maraging steel at room temperature.

At room temperature, fretting wear with Inconel 600 rubbing against itself was less than that with Inconel 600 rubbing against maraging steel. In comparison with room-temperature experiments, at 500° F (260° C) the fretting wear of Inconel 600 rubbing against itself is low, as is the wear of all other material combinations at that temperature. The molten sodium hydroxide oxidized Inconel 600 rubbing against itself showed

the lowest fretting wear at room temperature of all experiments run.

In the experiments reported, the use of the oxidized surface films to reduce fretting wear proved beneficial, which was mostly the result of the capability of nickel oxide (NiO) to minimize surface adhesion between contacting metals. The useful high friction is related to the high shear strength of the NiO film.

Experiments suggest that films formed by the molten sodium hydroxide oxidation process were most promising. However, films formed by the high-temperature oxidation process were also useful. The result for the latter process is particularly significant because such an oxide film can be regenerated in the high-temperature air of an advanced engine compressor.

The concept of achieving both high friction and low fretting wear by the utilization of a high-shear-strength surface film merits continued attention as other materials are considered for compressor blades, blade inserts, and damping wires. Although other types of friction dampers will have different friction and wear problems, the fretting phenomenon, however, will be a common problem for all types of vibration dampers.

SUMMARY OF RESULTS

The investigation of friction and fretting wear of Inconel 600 wire with and without preformed oxides was conducted at both room temperature and 500° F (260° C). The following results were obtained:

1. Molten sodium hydroxide oxidized nickel alloys (e. g. , Inconel 600) rubbing against maraged steel at room temperature provided the desired high friction and low wear for compressor blade damping.
2. Further improvement in wear was made in fretting experiments with oxidized material (Inconel 600) rubbing against itself rather than against the maraged steel. Thus, compressor blade inserts would be advantageous in achieving the most efficient damping.
3. The results of friction and wear tests for titanium - 6 aluminum - 4 vanadium alloy rubbing against itself differed with respect to temperature.
 - a. The friction was high at both room temperature and 500° F (260° C).
 - b. The wear was low at 500° F (260° C) as compared with that at room temperature.

4. The friction and wear for all materials were lower at 500⁰ F (260⁰ C) than at room temperature.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 19, 1968,
720-03-01-01-22.

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